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A METHOD FOR THE DESIGN OF COOLING SYSTEMS FOR AIRCRAFT POWER-PLANT INSTALLATIONS

By Kennedy F. Rubert and George S. Knopf

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

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A METHOD FOR THE DESIGN OF COOLING SYSTEMS FOR AIRCRAFT POWER-PLANT INSTALLATIONS

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L-491

INTRODUCTION

A method of organizing design calculations for the cooling systems of aircraft power-plant installations has been developed for use by representatives of airplane and engine companies invited by the Matériel Division, Army Air Corps Liaison Office to participate in the activities of the NACA power-plant installation section at the Langley Memorial Aeronautical Laboratory, Langley Field, Va.

A schematic arrangement of a heat exchanger with a cooling-air duct is shown in figure 1. The system consists of three parts: (1) the entrance duct, which slows down the cooling air and converts most of its dynamic pressure to static pressure; (2) the heat exchanger, in which some of the static pressure is lost; and (3) the exit duct, which converts to dynamic pressure any surplus of static pressure above the value at the exit.

At station 0 in the free stream ahead of the entrance, the air has a static pressure P_0, a velocity V_0 relative to the duct, and a dynamic pressure q_0. As the air approaches the entrance at station 1, its velocity decreases, and the dynamic pressure is partly converted to static pressure. From station 1 to station 2 the velocity continues to decrease, usually to the point where the dynamic pressure is negligible, with a corresponding further increase in static pressure. As a result of the losses in the entrance section, the increase in static pressure from station 0 to station 2 is less than the decrease in the dynamic pressure.

The air on entering the heat exchanger is accelerated because of the reduction in free area and on leaving is decelerated to a velocity equal to the velocity at station 2. The internal resistance of the heat exchanger causes a relatively large loss of static pressure.

From station 3 to the outlet the static pressure drops to that of the free stream, and the dynamic pressure rises to a value less than that of the free-stream dynamic pressure by an amount equal to the sum of the losses of the entire system.

The addition of heat to the cooling air in the heat exchanger makes no change in these fundamental principles; but, in the calculation of the internal horsepower and the exit area, the effect of the heat on the density of the air must be taken into account.

SYMBOLS

A	duct cross-sectional area, square feet
F_c	compressibility factor
M	weight rate of air flow, pounds per second
P	static pressure, pounds per square foot
ΔP	pressure loss, pounds per square foot
Q	volume rate of air flow, cubic feet per second
T	temperature, °F absolute
ΔT	temperature rise, °F
V	velocity, feet per second
g	acceleration of gravity, feet per second per second
q	dynamic pressure, pounds per square foot
ρ	mass density, slugs per cubic foot
σ	relative density $\frac{\rho}{0.002378}$
w	width

Subscripts:

0, 1, 2, 3, 4 station numbers as in figure 1

ILLUSTRATIVE EXAMPLES

Computations selected from an analysis made in conjunction with one of the designs developed by members of the NACA power-plant installation section are used to demonstrate the system of calculations. Design values that occur throughout the example have been selected for the particular design under consideration; where possible, references are listed for selecting similar values for other types of design.

The power-plant installation was designed for a long-range bomber, powered by four 2000-horsepower engines equipped with turbosuperchargers. The pertinent data for the engines are given in table I and for the airplane performance are given in table II.

A general arrangement of the power-plant installation is shown in figure 2. All cooling and charge air is taken in at the nose of the cowling. Air for the supercharger intake, oil coolers, and intercoolers enters through the outer annulus and flows through ducts distributed around the periphery of the engine. Cooling air for the engine flows through the inner annulus over the engine and is discharged through outlets between the charge-air and the cooling-air ducts.

All cooling calculations are based on Army summer air, which has the same pressure as standard air (reference 1) but has a temperature 40° F greater than standard throughout the range considered. Properties of this air are given in table III.

Engine Cooling System

Detailed computations for the engine cooling system at the high-speed condition, under normal rated power at 20,000 feet, are presented in form A, which is the master form suggested for use on all cooling systems of the power-plant installation. The free-air conditions for pressure, temperature, and density are first selected from table III for station 0 and entered in the form

$$P_0 = 972 \text{ lb/sq ft}$$

$$T_0 = 487° \text{ F abs.}$$

$$\rho_0 = 0.001160 \text{ slugs/cu ft}$$

From table II for 20,000 feet the high speed in Army air under normal power is 358 miles per hour, corresponding to $V_0 = 525$ feet per second. The dynamic pressure is

$$q = \frac{1}{2} \rho V_0^2 F_c$$

where the compressibility factor F_c derived from reference 2 is given by the relation

$$F_c = 1 + 1.035 \frac{(V_0/100)^2}{T_0} + 0.422 \left[\frac{(V_0/100)^2}{T_0}\right]^2 + \ldots$$

Therefore

$$F_c = 1 + 1.035 \frac{(5.25)^2}{487} + 0.422 \left[\frac{(5.25)^2}{487}\right]^2 = 1.063$$

and

$$q_c = \frac{1}{2} 0.001160 \times (525)^2 \times 1.063 = 170 \text{ lb/sq ft}$$

Station 1 has been included in order to provide in certain flight conditions for an increase in pressure through the propeller or for a detailed analysis of the losses for a complicated inlet duct. For the case at hand, the computations of the values for this station are unnecessary.

The properties of the cooling air in front of the engine at station 2 are now required to determine the amount of air necessary for engine cooling. Inasmuch as the dynamic pressure at station 2 is small, the computations may be simplified by assuming that all dynamic pressure exclusive of duct losses is converted to static pressure.

The two columns in form A under the heading Transition are for recording the changes that occur between the preceding station and the station under consideration. The column headed ΔP gives only the losses of total pressure; conversions of dynamic pressure to static pressure or vice versa are not included in the values in this column. The column for ΔT shows values for the change in temperature, regardless of cause, and includes both adiabatic changes and changes due to heat transfers.

For the entrance duct used in the design it is probable that approximately 90 percent of the free-stream dynamic pressure can be converted to static pressure at the front face of the engine. In other words, the entrance-diffuser loss is estimated to be 10 percent of the free-stream dynamic pressure, 17 pounds per square foot. Accordingly,

$$P_2 = 972 + 170 - 17 = 1125 \text{ lb/sq ft}$$

The temperature rise due to adiabatic compression of the air in the diffuser inlet can be expressed in terms of the velocities alone

$$\Delta T_{0-2} = 0.832 \left[\left(\frac{V_o}{100} \right)^2 - \left(\frac{V_2}{100} \right)^2 \right]$$

This expression is derived from reference 3.

As previously noted, V_2 is negligible, and the temperature rise used for the computation is

$$0.832 \left(\frac{V_o}{100} \right)^2 = 0.832 \ (5.25)^2 = 23^\circ \text{ F}$$

Hence, the absolute temperature of the air at the front face of the engine is

$$T_2 = 487 + 23 = 510^\circ \text{ F abs.}$$

The mass density of the air may now be computed from standard sea-level density as follows:

$$\rho_2 = 0.002378 \times \frac{P_2}{2116} \times \frac{518.4}{T_2}$$

$$= 0.000583 \frac{P_2}{T_2} = 0.001285 \text{ slugs/cu ft}$$

The various engine manufacturers use different methods for arriving at the amount of cooling air required and the corresponding pressure drop. All these methods, however, require a knowledge of the condition of the air at the front of the engine. A typical example of such a method is to be found in reference 4. For the case of form A the required air flow is 37.3 pounds per second and the corresponding pressure drop is 51 pounds per square foot.

The computation of the velocity at the face of the engine is now possible. In this case the velocity is found to be about 60 feet per second, not enough to make any appreciable change in the static pressure (-2.3 lb/sq ft) or in the absolute temperature (-0.3° F abs.) at the face of the engine; hence, the dashes in the table indicate that the quantities regarded as zero are allowed to stand.

Behind the engine at station 3, the transition column shows the 51 pounds per square foot pressure drop given by the manufacturer and, inasmuch as the dynamic pressure is negligible, $P_3 = P_2 - \Delta P_{2-3}$ = 1125 - 51 = 1074 pounds per square foot. The temperature change is obtained by dividing the heat rejection from the engine (25,000 Btu per min specified by manufacturer) by the specific heat of air and the weight rate of air flow.

$$\Delta T = \frac{25000}{60} \times \frac{1}{0.24} \times \frac{1}{37.3} = 47° \text{ F}$$

and

$$T_3 = T_2 + \Delta T = 510 + 47 = 557° \text{ F abs.}$$

It is unnecessary to evaluate the density at this station.

The pressure loss from station 3 to station 4 is estimated to be 5 percent of q_o or 8.5 pounds per square foot. For simplicity, it is assumed that the exit process consists of a pressure loss without change of temperature followed by an adiabatic expansion. The air is therefore regarded as expanding adiabatically from a temperature of 557° F and a pressure of 1074 - 8.5 = 1065.5 pounds per square foot to free-stream static pressure at the exit, 972 pounds per square foot. From the thermodynamic properties of perfect gases, the absolute temperature at the end of such an expansion is the product of the initial temperature and the 0.286 power of the ratio of final to initial pressures

$$T_4 = 557 \left(\frac{972}{1065.5} \right)^{0.286} = 542.56^\circ \text{ F abs.}$$

a temperature drop of 14.44° F.

The satisfactory evaluation of the exit velocity requires an accuracy of four significant figures in the value of ΔT and necessitates the use of logarithms. As this process is adiabatic, the exit velocity can be obtained directly from the temperature drop, and

$$T_{3-4} = -0.832 \left(\frac{V_4}{100} \right)^2$$

$$V_4 = 100 \sqrt{\frac{14.44}{0.832}} = 416.8 \text{ ft/sec}$$

Upon determination of the density of the air at the exit and by use of the previously obtained weight-flow rate, the volume-flow rate is found to be 1110 cubic feet per second. At the exit velocity of 416.8 feet per second, an exit area of 2.66 square feet is required.

The internal power consumption of the engine cooling system is obtained from the rate of change of momentum of the cooling air.

$$\frac{\text{weight/sec}}{32.2} \times \frac{V_o \, (V_o - V_4)}{550} = \frac{37.3}{32.2} \times \frac{525 \, (525 - 416)}{550} = 121 \text{ hp}$$

Owing to the manner in which the power has been computed, the Meredith effect due to the addition of heat is included. A discussion of the relation of Meredith effect to cooling horsepower is given in reference 5.

The results of similar calculations on this and other operating conditions over an altitude range from sea level to 25,000 feet are given in tables IV, V, and VI. The variation of engine cooling-air exit area with altitude and condition of flight is presented graphically in figure 3.

Oil Cooler

It is necessary to select an oil cooler before proceeding with the analysis of the system containing the cooler. Because an oil cooler adequate for climb at sea level is usually satisfactory for all other flight conditions, a preliminary choice is made on this basis.

Data on commercial oil coolers are often presented in curve form, as shown in figure 4. The curves show the heat transfer

$$\frac{\text{Btu/min}}{\text{100° F temp. diff., av. oil and entering air}}$$

plotted against cooling-air flow in pounds per minute for several rates of oil flow. An additional curve shows the pressure drop required to produce any flow rate of standard sea-level air. For any other condition the pressure drop is determined by dividing the value obtained from the curve by σ_3, the relative density of the air at the face of the cooler.

The engine specifications in table I call for a heat rejection to the oil at military power of 6500 Btu per minute and for a temperature of 185° F for oil returning to the engine. The rate of oil flow is 135 pounds per minute. With an assumed specific heat for the oil of 0.5 Btu per pound per °F, the temperature drop of the oil through the cooler is 96° F and the average cooler temperature is 692° F, absolute. The temperature of the air at the cooler face, obtained in the same way as in the engine cooling example, is 563° F. Inasmuch as two oil coolers which are similar with regard to both air and oil flow are to be used, the heat transfer for each unit is

$$\frac{6500/2}{(692 - 563)/100} = \frac{2520 \text{ Btu/min}}{100° \text{ F diff.}}$$

and the rate of oil flow per unit is 67.5 pounds per minute. From figure 4 an air flow of 415 pounds per minute is required with a pressure drop of 7 inches of water in standard sea-level air. Inasmuch as the density of the air at the cooler face relative to standard sea-level air is 0.947, the actual pressure drop is

$$\frac{7}{0.947} = 7.4 \text{ in. water} = 38.5 \text{ lb/sq ft}$$

From this point on, the analysis for determining the duct exit area and the internal horsepower is precisely the same as that for the engine cooling-air system. Tables IV, V, and VI include the results of the computations for all flight conditions considered; exit areas are shown in figure 5.

Intercooler

Two factors mainly determine the selection of an intercooler; the weight rate of flow of engine charge air and the required intercooler effectiveness. The effectiveness is defined as the ratio of the temperature drop of the engine charge air as it goes through the cooler to the temperature difference between the hot charge air and the cooling air as they enter the cooler.

The temperatures of the air entering the supercharger and the cooling air entering the intercooler are determined in the same manner as is the temperature of the air at the face of the engine.

The absolute temperature of the air leaving the supercharger T_b is obtained from the relation

$$T_b = T_a \left\{ 1 + \frac{1}{\eta_{ad}} \left[\left(\frac{P_b}{P_a} \right)^{0.286} - 1 \right] \right\}$$

where

T_a	absolute temperature of air entering supercharger
P_a	total pressure of air entering supercharger
P_b	total pressure of air leaving supercharger
η_{ad}	temperature ratio efficiency of supercharger

As an example, consider the climb for normal rated power at 25,000 feet in Army air, the tabular computations for which appear in form B. The air at the entrance to the supercharger has a pressure of 855 pounds per square foot and a temperature of 482° F. From table I the required carburetor pressure for normal rated power is 28.1 inches of mercury. An allowance of 1.35 inches of mercury is made for pressure losses from the supercharger outlet through the intercooler to the carburetor inlet, making the necessary supercharger outlet pressure 29.45 inches of mercury or 2081 pounds per square foot. With a temperature efficiency ratio of 0.65, the supercharger outlet temperature is

$$482 \left\{ 1 + \frac{1}{0.65} \left[\left(\frac{2081}{855} \right)^{0.286} - 1 \right] \right\} = 699° \text{ F abs.}$$

The required carburetor temperature from table I is 100° F (559° F abs.) and the cooling air at the entrance of the intercooler is 482° F absolute. The required effectiveness is therefore

$$\frac{T_{\text{supercharger outlet}} - T_{\text{carburetor}}}{T_{\text{supercharger outlet}} - T_{\text{cooling-air inlet}}} = \frac{699 - 559}{699 - 482} = 0.645$$

At normal power the charge-air consumption, which must be cooled to this effectiveness, is 3.88 pounds per second. The number of possible intercoolers to meet these conditions is unlimited but is successively narrowed down to meet conditions of pressure drop available, space limitation, and power required. The unit investigated measures 8 inches in the direction of cooling-air flow, 14 inches in the direction of charge-air flow, and 41.5 inches in the no-flow direction. Characteristics of this unit applicable to any no-flow length are presented in figure 6. (An explanation of this type of curve is given in reference 6, together with similar curves for a variety of intercoolers. Charts for the design of certain types of tubular intercooler are given in references 7 and 8.) Entering with a charge flow per inch of width of 3.88 pounds per second ÷41.5 inches = 0.0935 pound per second per inch gives $\sigma_{2_{av}}\Delta P_2$ for the charge air, a value of 5.6 inches of water. The intersection of this value with a cooler effectiveness of 0.645 indicates $\sigma_{1_{av}}\Delta P_1$ for the cooling air, a value of 3.98 inches of water and a cooling-air flow rate of 0.19 pound per second per inch, or 7.98 pounds per second, making the ratio of cooling-air flow to charge-air flow 0.19/0.0935 = 2.04. The temperature rise of the cooling air is the temperature drop of the charge air divided by the ratio of cooling air to charge air; $\frac{140}{2.04} = 68.5°$ F, and the mean temperature of the air is the temperature at the entrance plus one-half this temperature rise, 482 + 34.3 = 516° F absolute. Corresponding to this temperature and to a pressure at the entrance of 855 pounds per square foot, the average relative density of the cooling air $\sigma_{1_{av}} = 0.405$, and the actual pressure drop of the cooling air is $\frac{\sigma_{1_{av}}\Delta P_1}{\sigma_{1_{av}}} = \frac{3.98}{0.405} = 9.82$ inches of water, or 51.1 pounds per square foot.

With the foregoing information it is now possible to compute the velocity of the cooling air at the exit and the area of the exit as was done for the engine-cooling system. About 76 percent of the original dynamic pressure for the climb condition under consideration has been expended in pressure losses by the time the air arrives at the rear of the intercooler. The exit velocity to be created with the remaining energy is so low that excessively large exit areas would be

required. Extension of exit flaps decreases the static pressure at the duct exit, making available a greater pressure difference for expelling the air, which creates a higher exit velocity and makes a more reasonable exit area possible. The analysis from this point on differs from previous cases having unextended flaps in that the pressure at the exit (station 4) is subatmospheric by a flap boost estimated to be $0.2q_0$ (16 lb/sq ft). Because of the large external drag effects in operation with extended flaps, internal horsepower calculations in this case are regarded as of little or no value. Some experimental measurements of the influence of flaps on the pressure at the exit and drag of the airplane are given in reference 9.

The curves of exit area as a function of flight condition and altitude in figure 7 show that the intercooler investigated is satisfactory for operation at normal rated power but is inadequate for military rating. The need for a larger intercooler capable of meeting the military rating is apparent. If it is found undesirable to increase the no-flow length of the unit, it will be necessary to investigate a different type of core.

Duct Inlet Area

Exit areas are designed to control the rate of flow of air through cooling ducts. The area of the duct inlet is based on the ratio of inlet velocity to flight velocity V_1/V_0 found by experiment to be optimum with regard to the internal entrance loss and the external drag. In the selection of the inlet area it has been found convenient to plot curves of entrance area against the ratio V_1/V_0 for each main flight condition. As these curves are hyperbolic, they may be drawn as 45° straight lines on logarithmic paper, as shown for the example in figure 8.

For the main air inlet, which admits the charge air and all cooling airs, the two lines in figure 8 represent the extremes in areas required for high-speed and climb conditions with military power from sea level to 25,000 feet. As air inlets are usually of fixed area, the inclusion of flight conditions in standard air is necessary.

From aerodynamic considerations a minimum inlet-velocity ratio $\frac{V_1}{V_0} = 0.4$ is considered essential to the proper functioning of the cowling under consideration. The curves show that an inlet area of 4 square feet meets this requirement for standard air without excessive velocity ratios for climb in Army air. The special case of scoops is treated in reference 10.

CONCLUDING REMARKS

The analyses of design conditions for an intercooler and an oil cooler have been illustrated rather than the method of the selection of optimum units. Obviously, for a particular airplane the available sizes and types of heat exchangers should be considered in order to arrive at the best arrangement with due regard to the relative importance of the various factors involved. One such factor may be weight, or simply the drag horsepower associated with the weight, given by the relation

$$\text{weight-drag hp} = \text{weight} \times \frac{C_D}{C_L} \times \frac{V_\infty}{550}$$

where C_D/C_L is the ratio of the airplane drag to lift, and the weight is that of the cooler and ducts. The total horsepower chargeable to a cooling system is comprised of the weight horsepower, the internal horsepower as calculated in this report, and the external horsepower associated with the effect of the cooling system on the external air flow about the airplane. Wind-tunnel data are usually necessary for evaluation of the external horsepower.

Space limitations frequently override all other considerations in the selection of cooling units, often to the detriment of cooling characteristics as well as at the expense of additional power. The importance of selecting the cooling units in the very early stages of an airplane design in order to be able to install units that not only perform their function but perform it at a relatively low cost in horsepower cannot be overemphasized.

There is an ever-increasing demand for reliable prediction of cooling performance owing to the necessity of eliminating experimental airplanes and of proceeding immediately from the design to large-scale production. Because of this situation and the increase in the speeds and altitudes of flight, there is an urgent need for accurate and more extensive basic data on the characteristics of engines, superchargers, heat exchangers, and cooling-air ducts.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va.

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TABLE I - ENGINE DATA

Item	Military power	Normal rated power	0.7 normal rated cruise power
Brake output, hp	2200	2000	1400
Engine speed, rpm	2600	2400	2360
Carburetor pressure, in. Hg	29.8	28.1	
Carburetor temperature, °F	100	100	100
Air consumption, lb/min	262	233	172
Specific fuel consumption, lb/bhp-hr	0.76	0.70	0.50
Oil heat rejection, Btu/min	6500	5500	
Oil circulation, lb/min	135	130	
Oil temperature, °F	185	185	185
Maximum rear head temperature, °F	450	[a]425 [b]450	400
Effective baffle area, sq ft	3.2	3.2	3.2
Heat rejection from fins, Btu/min	28,000	25,000	23,800
Supercharger temperature ratio efficiency	0.65	0.65	0.65

[a]High Speed. [b]Climb.

L-491

TABLE II - PERFORMANCE DATA

Altitude (ft)	True airspeed, mph			
	Military power	Normal rated power		0.7 normal rated cruise power
	High speed	High speed	Climb	
0	303	291	170	259
3,000	314	301	178	268
6,000	325	311	186	276
10,000	339	324	198	288
15,000	357	341	215	303
20,000	375	358	235	318
25,000	393	375	268	333
30,000	410	391	327	347

TABLE III - PROPERTIES OF ARMY SUMMER AIR

Altitude (ft)	Static pressure, P_o (lb/sq ft)	Absolute temperature, T_o ($^\circ$F abs.)	Density, ρ (Slugs/ cu ft)
0	2116	558	0.002210
3,000	1895	548	.002015
6,000	1694	537	.001840
10,000	1453	523	.001620
15,000	1192	505	.001378
20,000	972	487	.001160
25,000	785	469	.000975
30,000	628	451	.000811

TABLE IV

HIGH SPEED - NORMAL RATED POWER

	Altitude, ft	0	3,000	6,000	10,000	15,000	20,000	25,000
M (lb/sec)	Engine cooling	51.00	48.30	47.00	44.00	40.70	37.30	34.40
	Oil cooling	13.33	11.50	———	8.84	———	6.77	———
	Intercooling	———	———	———	12.50	10.02	9.27	9.00
	Charge air	3.88	3.88	3.88	3.88	3.88	3.88	3.88
Q (cu ft/sec)	Engine cooling	675.0	697.0	740.0	780.0	842.0	902.0	978.0
	Oil cooling	197.8	187.4	———	180.0	———	194.6	———
	Intercooling	———	———	———	222.0	207.0	224.0	256.0
	Charge air	51.4	56.1	61.1	68.9	80.1	93.0	110.5
ΔP (lb/sq ft)	Engine cooling	52.0	51.0	52.0	52.0	52.0	51.0	51
	Oil cooling	34.9	28.8	———	21.2	———	18.3	———
	Intercooling	———	———	———	64.0	53.0	53.0	60
A_4 (sq ft)	Engine cooling	2.220	2.230	2.280	2.400	2.520	2.660	2.880
	Oil cooling	.544	.488	———	.414	———	.412	———
	Intercooling	———	———	———	.706	.622	.667	.801
Internal horsepower (hp)	Engine cooling	101.0	101.00	98.0	108.50	111.3	121.00	128.0
	Oil cooling	20.2	15.82	———	12.10	———	10.64	———
	Intercooling	———	———	———	40.60	31.1	31.60	38.3

TABLE V

CLIMB - NORMAL RATED POWER

	Altitude, ft	0	3,000	6,000	10,000	15,000	20,000	25,000
M (lb/sec)	Engine cooling	41.50	39.70	38.00	36.00	33.00	30.50	28.00
	Oil cooling	11.66	10.16	------	7.83	------	6.33	------
	Intercooling	------	------	6.60	6.80	7.00	7.45	7.93
	Charge air	3.88	3.88	3.88	3.88	3.88	3.88	3.88
Q (cu ft/sec)	Engine cooling	573.0	599.0	625.0	665.0	719.0	780.0	844.0
	Oil cooling	172.8	165.2	------	159.8	------	182.0	------
	Intercooling	------	------	108.8	126.6	152.5	190.1	239.0
	Charge air	53.5	58.5	63.9	72.3	84.5	99.2	116.9
ΔP (lb/sq ft)	Engine cooling	36	36.0	36.0	36.0	36.0	36.0	36.0
	Oil cooling	28	23.4	------	18.5	------	16.3	------
	Intercooling	------	------	19.9	24.0	29.6	37.6	51.1
A_4 (sq ft)	Engine cooling	4.250	4.290	4.300	4.380	4.360	4.250	3.870
	Oil cooling	1.014	.878	------	.700	------	.646	------
	Intercooling	------	------	.475	.541	.662	.821	1.096
Internal horsepower (hp)	Engine cooling	59.0	62.00	63.5	68.40	73.40	76.00	80.0
	Oil cooling	13.0	10.94	------	7.96	------	7.78	------
	Intercooling	------	------	------	------	------	------	------

TABLE VI

HIGH SPEED - MILITARY POWER

	Altitude, ft	0	3,000	6,000	10,000	15,000	20,000	25,000
M (lb/sec)	Engine cooling	43.60	42.40	40.00	37.70	34.50	32.40	30.30
	Oil cooling	17.00	14.83	------	11.13	------	8.10	------
	Intercooling	------	------	------	------	16.00	13.55	12.82
	Charge air	4.37	4.37	4.37	4.37	4.37	4.37	4.37
Q (cu ft/sec)	Engine cooling	575.0	608.0	626.0	665.0	707.0	775.0	851.0
	Oil cooling	251.6	240.6	------	226.4	------	232.0	------
	Intercooling	------	------	------	------	390.0	401.0	472.0
	Charge air	57.7	62.7	68.4	77.1	89.6	104.5	122.8
ΔP (lb/sq ft)	Engine cooling	38	39	38	38.0	37.0	38.0	39.0
	Oil cooling	53	44	------	32.3	------	25.7	------
	Intercooling	------	------	------	------	116.5	102.0	109.9
A_4 (sq ft)	Engine cooling	1.740	1.770	1.80	1.860	1.89	2.060	2.24
	Oil cooling	.706	.628	------	.528	------	.478	------
	Intercooling	------	------	------	------	1.34	1.230	1.59
Internal horsepower (hp)	Engine cooling	65.6	64.00	68.7	70.00	64.0	73.40	78
	Oil cooling	37.4	29.24	------	21.60	------	16.38	------
	Intercooling	------	------	------	------	110.0	94.30	117

FORM A .- FORM FOR DESIGN CALCULATIONS FOR ENGINE COOLING

Airplane _____ Analysis condition ARMY AIR _____ Unit analyzed ENGINE COOLING

Engine _____ Specification _____ Date _____

Station	Transition		Flight condition HIGH SPEED FOR NORMAL RATED POWER Altitude 20,000 FEET									
	Pressure losses, ΔP (lb/sq ft)	Temperature change, ΔT ($^{\circ}F$)	Velocity, V (ft/sec)	Pressure, P (lb/sq ft)	Temperature, T ($^{\circ}F_{abs}$)	Density, ρ (slugs/cu ft)	Relative density, σ	Specific weight, ρg (lb/cu ft)	Dynamic pressure, q (lb/sq ft)	Air flow, M (lb/sec)	Air flow, Q (cu ft/sec)	Cross-sectional area, A (sq ft)
0			525	972	487	0.001160			170			
2	17	23	—	1125	510	.001285			—	37.3	902	
3	51	47	—	1074	557				—			
4	8.5	-14.44	416.8	972	542.56	.001044			935	37.3	1110	2.66
					INTERNAL HORSEPOWER 121							

FORM 8 - FORM FOR DESIGN CALCULATIONS FOR INTERCOOLER

Airplane _____ Analysis condition ARMY AIR _____ Unit analyzed INTERCOOLER _____

Engine _____ Specification _____ Date _____

Station	Transition		Flight condition CLIMB FOR NORMAL RATED POWER Altitude 25,000 FEET									
	Pressure losses, ΔP (lb/sq ft)	Temperature change, ΔT ($^\circ F$)	Velocity, V (ft/sec)	Pressure, P (lb/sq ft)	Temperature, T ($^\circ F_{abs}$)	Density, ρ (slugs/cu ft)	Relative density, σ	Specific weight, ρg (lb/cu ft)	Dynamic pressure, q (lb/sq ft)	Air flow, M (lb/sec)	Air flow, Q (cu ft/sec)	Cross-sectional area, A (sq ft)
0			393	785	469	0.000975	0.410		78			
2	8	13.0	—	855	482	.001032	.434		—	7.93	239	
3	51	68.5	—	804	551	.000850	357		—			
4	4	-6.2	273	769	545	.000823	.346		31	7.93	299	1.096

L-1691

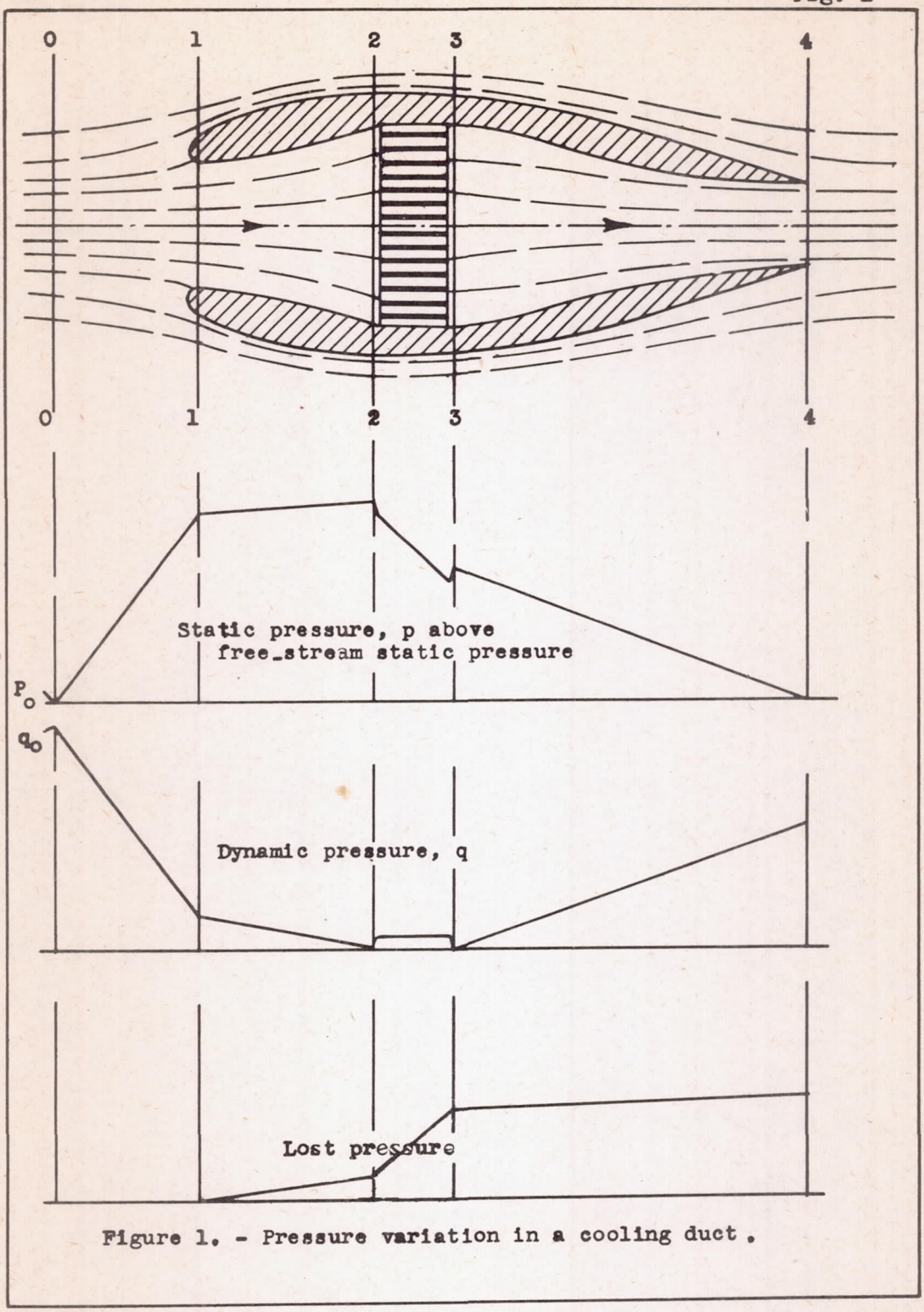
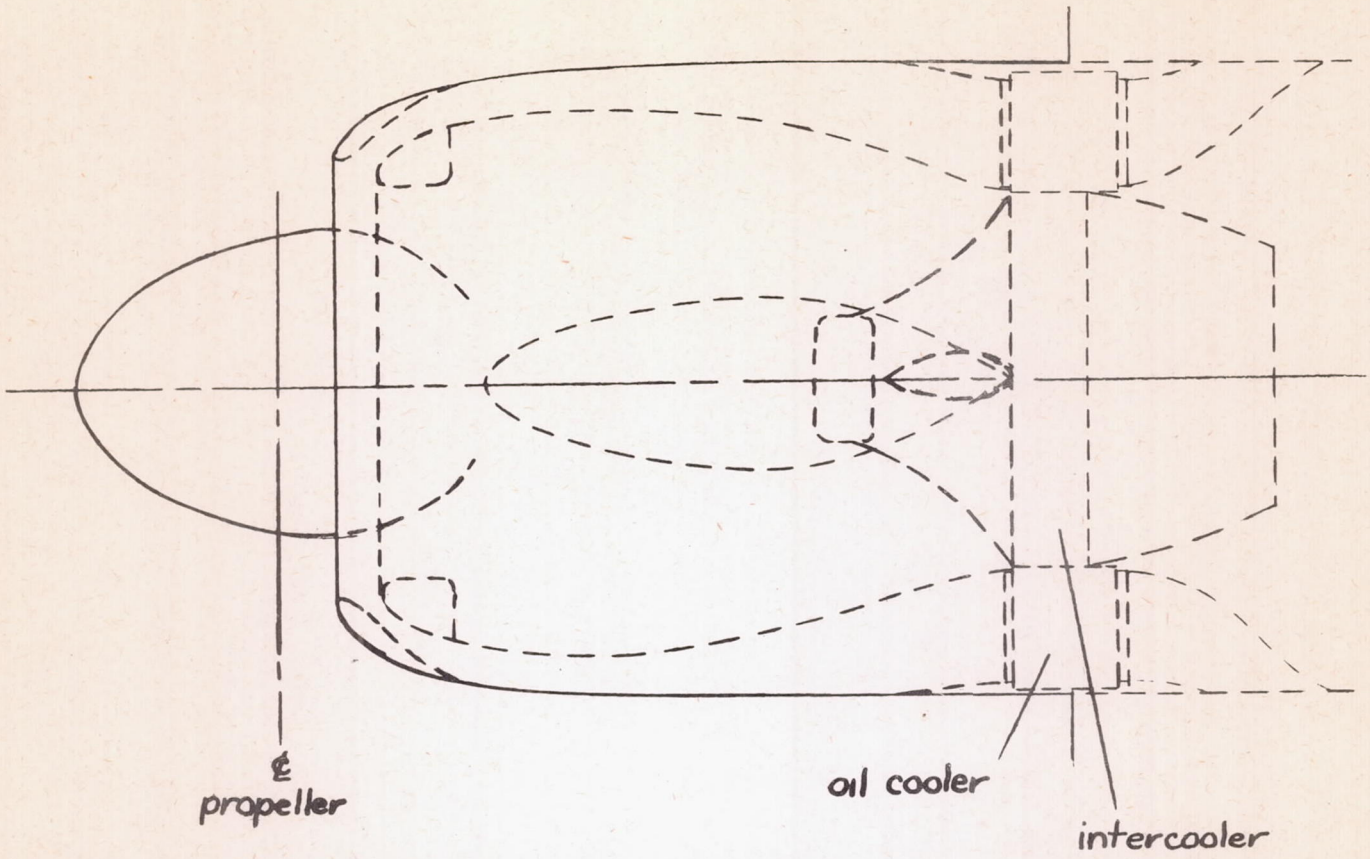


Figure 1. - Pressure variation in a cooling duct.



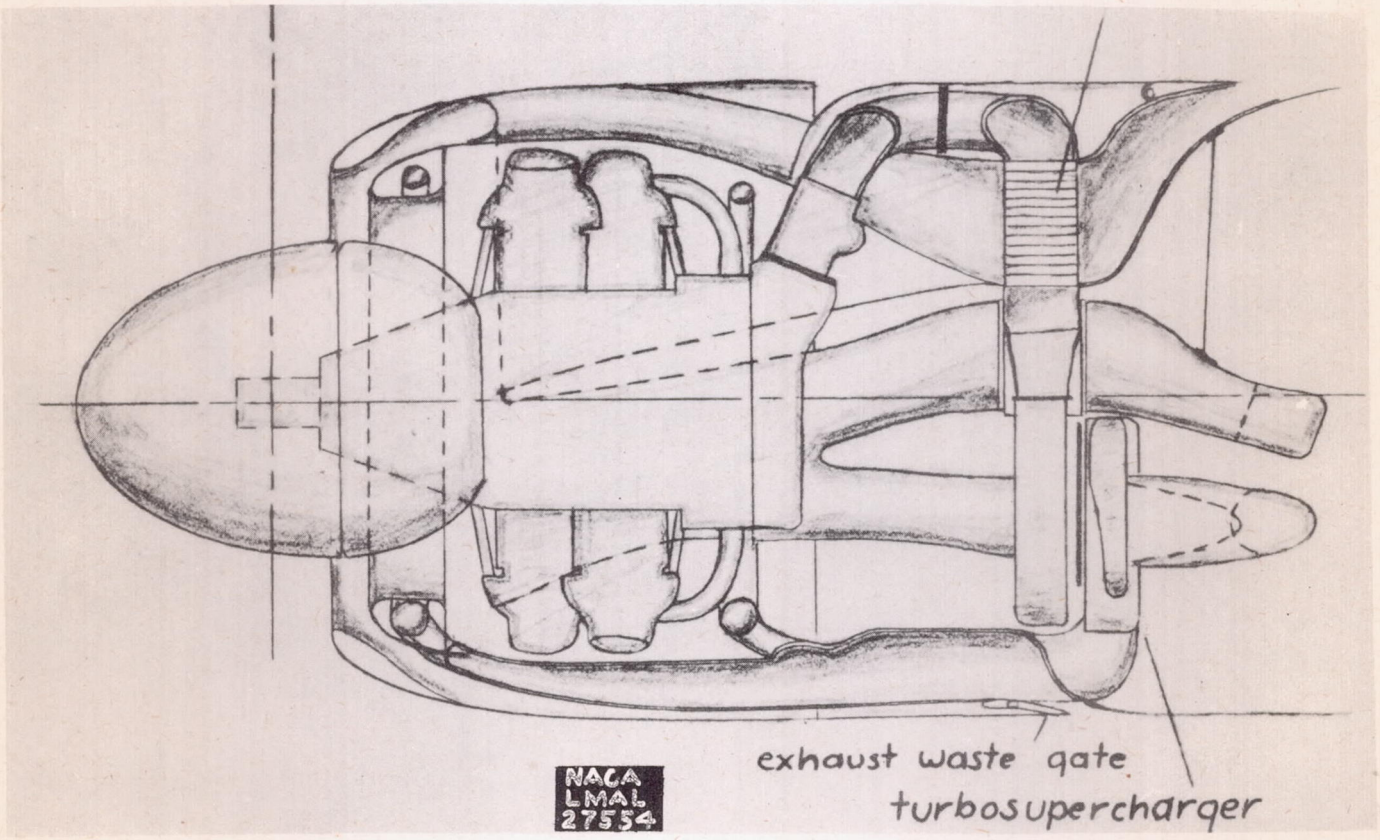


Figure 2.- Power plant installation.

L-491

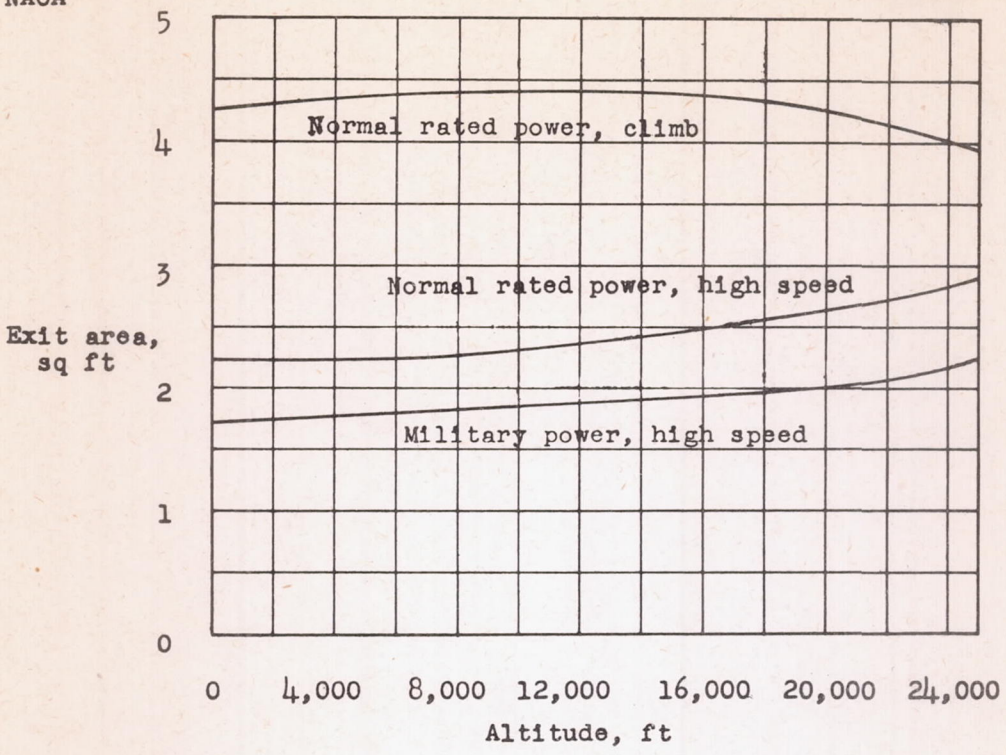


Figure 3.- Engine cooling-air exit area.

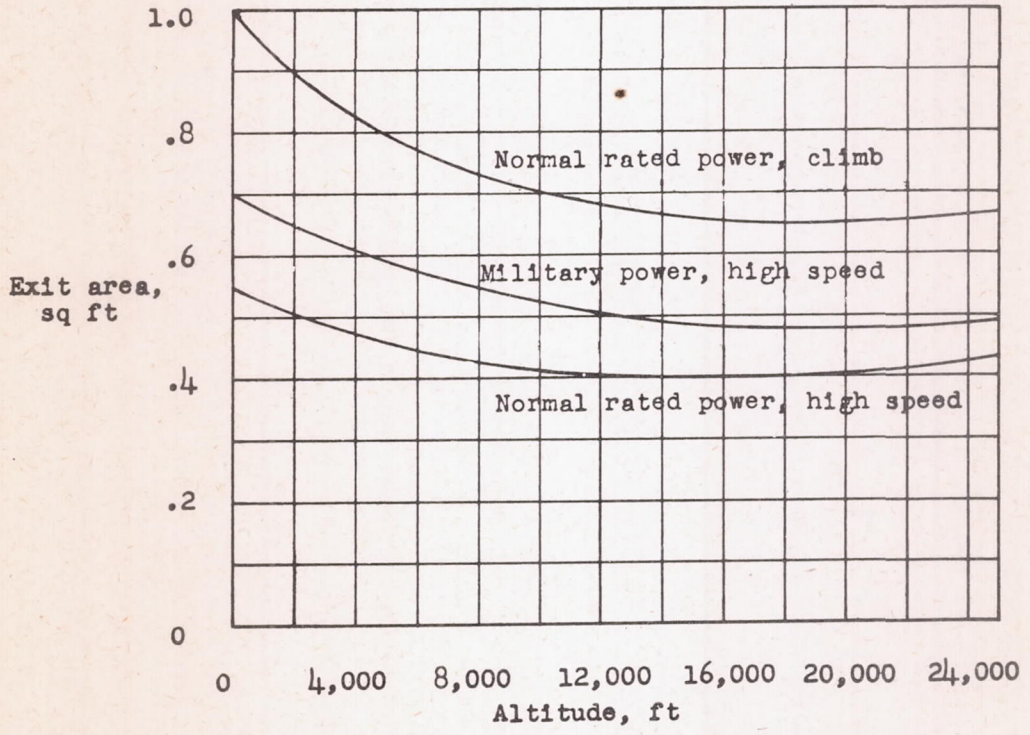


Figure 5.- Combined exit area for the two oil-cooler ducts.

L-764

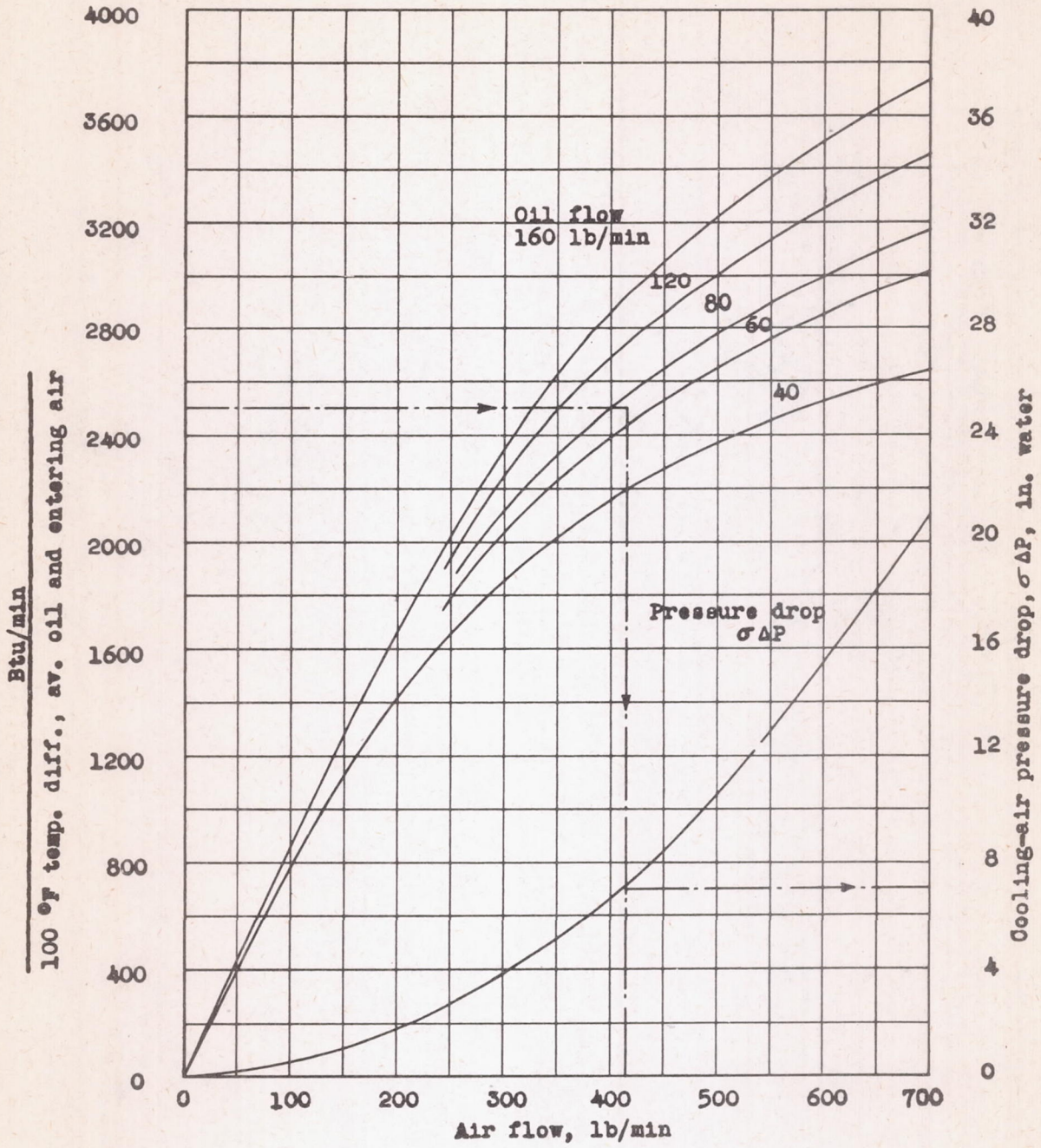


Figure 4.- The characteristics of an oil cooler. Diameter, 13 inches; depth, 9 inches.

L-491

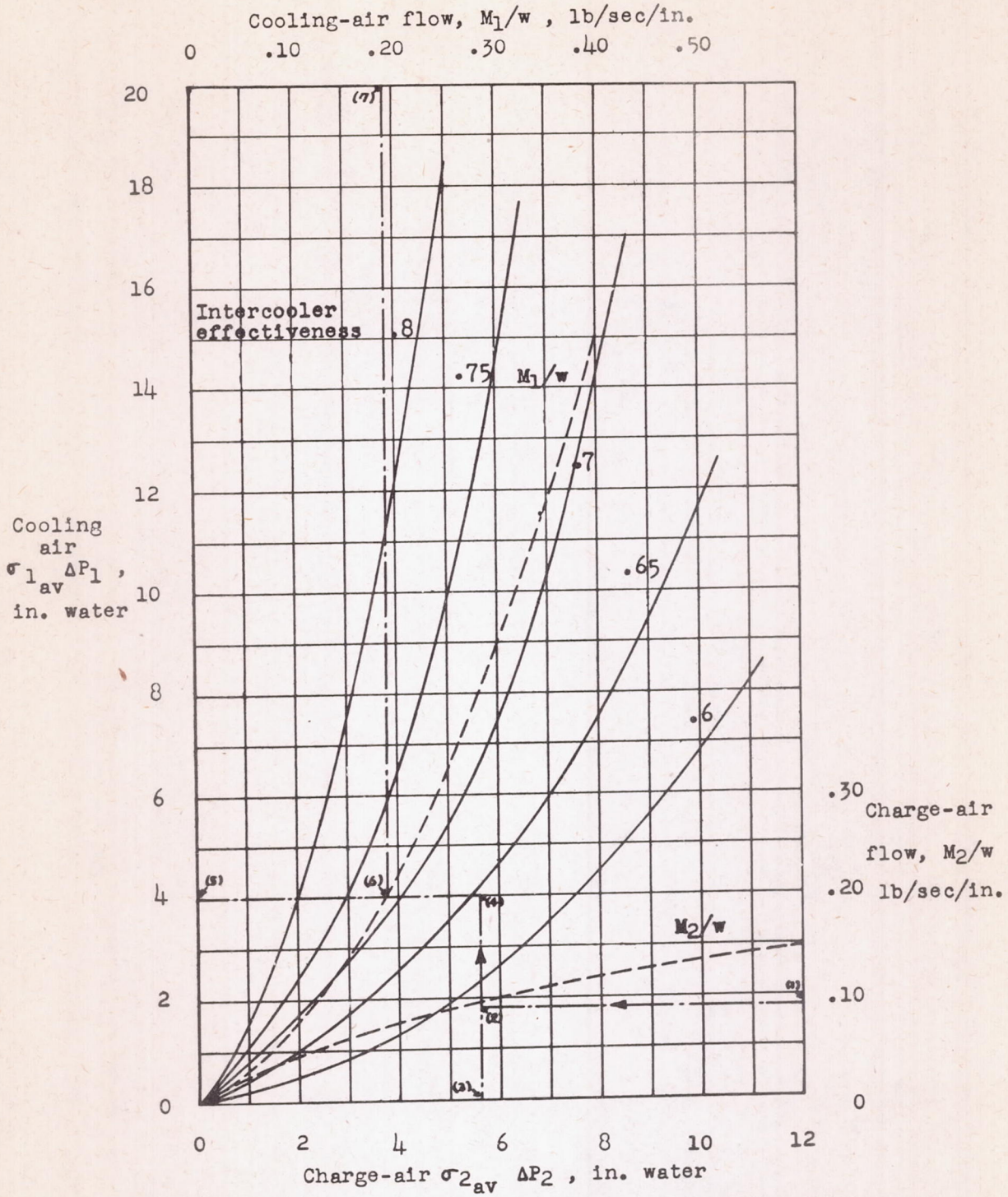


Figure 6.- Intercooler performance. Cooling length, 8 inches; engine length, 14 inches.

L-491

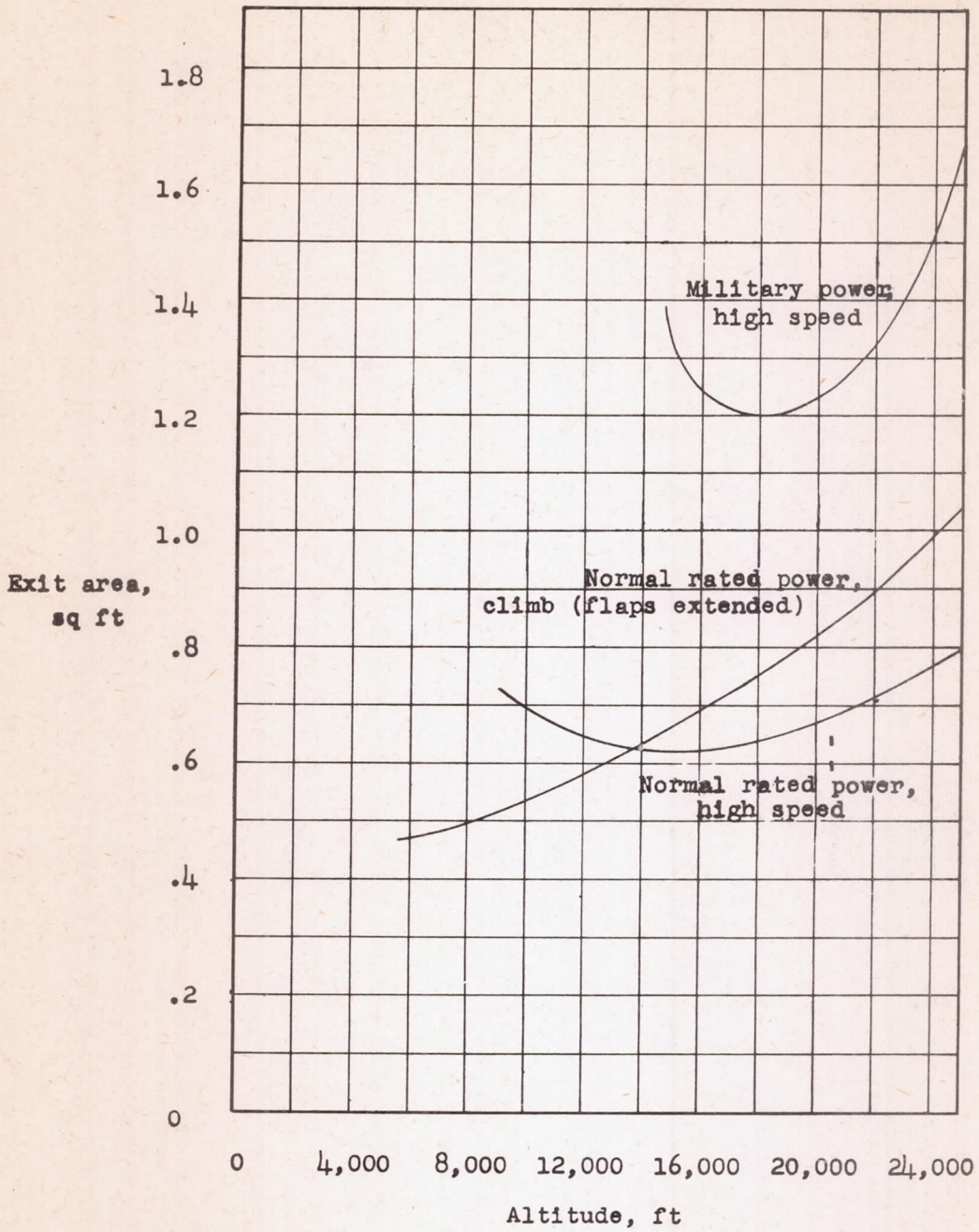


Figure 7.- Intercooler duct exit area.

L-491

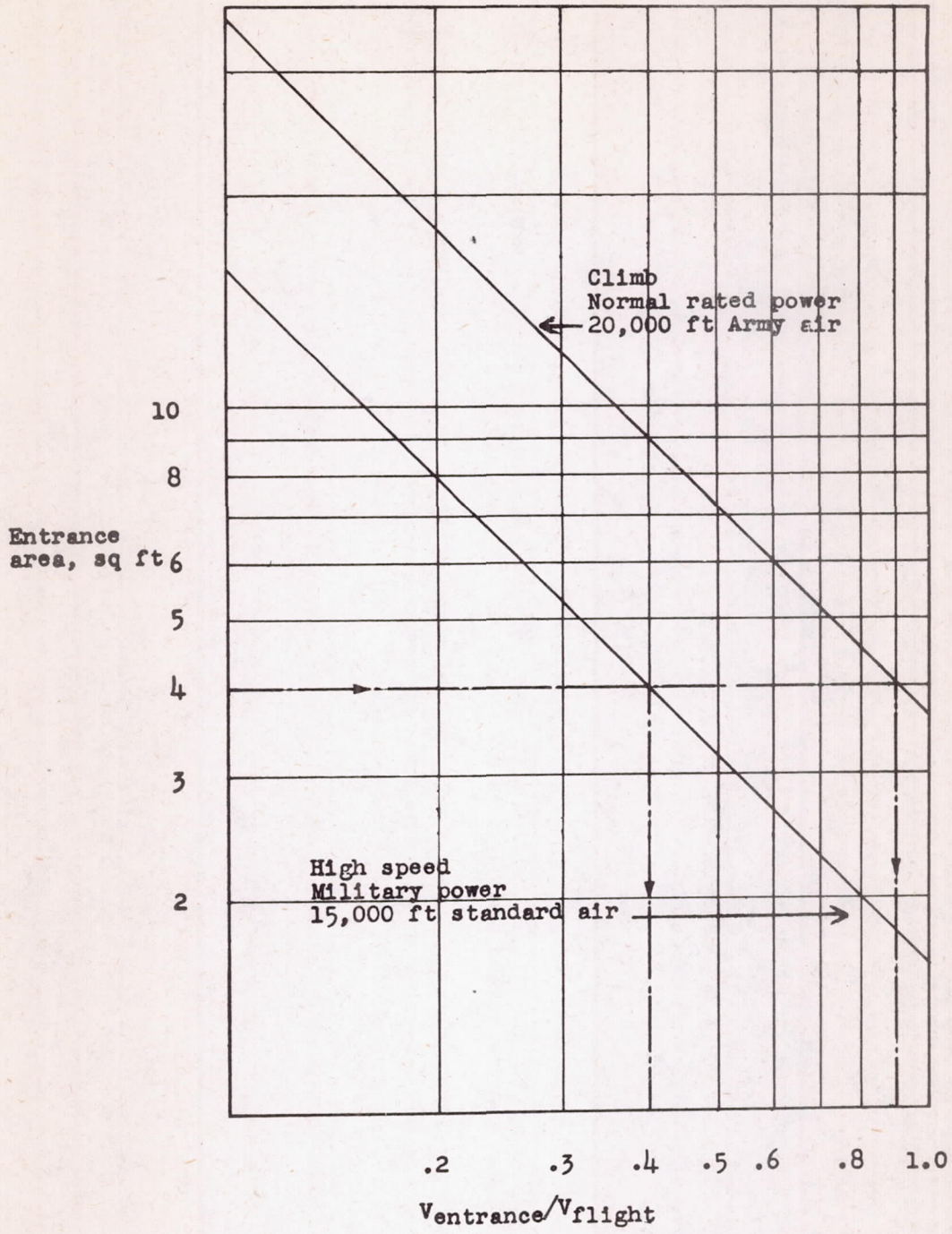


Figure 8.- Entrance-area selection curves.